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Foreword

no. 101

The behaviour of SF_6 puffer circuit-breakers under exceptionally severe conditions

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* The behaviour of SF_6 puffer circuit-breakers under exceptionally severe conditions

The development of transmission power systems and industrial power systems places high-voltage circuit-breakers in operating conditions much more severe than those taken into account by the Standards. Two situations are discussed:

- the case of very long lines for which difficulties encountered upon the energisation and de-energisation of no-load lines and upon shunt reactor switching are reviewed;
- the case of powerful transformers with low impedance voltage whose high natural frequency is at the origin of a severe transient recovery voltage when a fault takes place on the secondary side of the transformer.

In both cases, it is demonstrated that the SF_6 puffer circuit-breaker has a satisfactory behaviour though some of the conditions under consideration are exceptionally severe. It is generally unnecessary to resort to the use of auxiliary resistors, except for the energisation of long HV lines.

*Report number 13.08 presented at CIGRE, Conférence Internationale des Grands Réseaux Electriques (International Conference on Large High Voltage Electric Systems), session in 1978.

Contents

1 Introduction

The knowledge of the operation of high-voltage transmission systems and of the phenomena taking place on them upon operation of their protective circuit-breakers has been steadily progressing over the last twenty years. The theoretical study of operating requirements, the analysis of failures and CIGRE work have resulted in the recapitulation of all the conditions which must be taken into account for the design and verification of the switching devices intended to be used in high-voltage power systems. In the end, the process has been materialized by the inclusion of these switching conditions within the scope of international standards whose volume and complexity reflect the extent of the work carried out, a few points being still object of active work.

However, from time to time, special situations not directly referring to the operating conditions covered by the standards may occur. For instance, the extensive application of hydro-electric resources in some countries, necessitating the installation of very long lines, explains why network designers have to define non-standardized conditions for the verification of circuit-breakers. These problems are discussed in the first part of this paper.

Exceptional conditions also affect some installations incorporating powerful transformers with low impedance voltage. These special installations generate heavy stresses for the circuit-breakers; these have not been taken into account in the standards because they differ too much from the severity conditions generally encountered by power system circuit-breakers. This second problem is dealt with in the second part of this paper.

In both cases, the stresses withstood by the circuit-breaker, as well as the test procedures applied to check the satisfactory behaviour of an SF_6 puffer circuit-breaker, are reviewed.

2 Long extra-high-voltage lines

The SF_6 gas puffer technology used long since in switchgear for high-voltage distribution systems has been progressively extended to the switchgear of extra-high-voltage power systems owing to its advantages [1].

The very good experience gained in the field so far has led system users to try and expand the numerous advantages of this switchgear to systems of higher voltages, in particular to the 525 kV systems which constitute the backbone of transmission systems of numerous countries in the american continent where the heavy powers to be conveyed and the remoteness of load centers have been in favour of the decision for such a high voltage level. It must be recalled that the choice of a high voltage level is not really advantageous unless provision has been made for limiting the temporary overvoltages and the switching surges likely to occur in a high-voltage system. Without this limitation, the additional cost of the insulation to be provided for the system that would have to withstand heavy overvoltages reduces to nothing the savings achieved with the reduction of losses.

The development of systems having rated voltages of 525 kV or above has therefore, in particular, necessitated the consideration of three operational conditions that are likely to generate the highest overvoltages:

- closing and reclosing of open-ended lines;
- line charging current switching at exceptionally high voltages;
- shunt reactor switching.

2.1 Energisation of open-ended lines

A circuit-breaker protecting a line may have to energize it under open-ended conditions. The overvoltages due to the reflection at the open end must absolutely be mastered. The overvoltage levels to be complied with are not covered by international standards at present and their specification remains within the province of the system designer. Among all the methods which have been suggested to limit closing surges, the simplest one consists in energising the line through a resistor chosen in compliance with the characteristics and length of the line.

The circuit-breakers able to protect 525 kV and 765 kV systems must therefore be equipped with auxiliary interrupters allowing the resistors to be inserted during a predetermined time. This servitude, quite practicable with air-blast circuit-breakers, is also suited for SF_6 puffer circuit-breakers. It is indeed possible, to the very simple mechanism of these circuit-breakers, to add a linkage system driving the resistor insertion contacts during a closing operation (see **Fig. 1**). These contacts automatically move back to their open position immediately after the main contacts have closed. Such a linkage system assures an excellent accuracy of the insertion times of the resistors upon closing.

The value of the resistor may be selected by measurements on mode1 networks or by calculation. In particular, measurements performed on a transient analyzer have made it possible to determine the maximum values of the resistors and the minimum insertion times to be

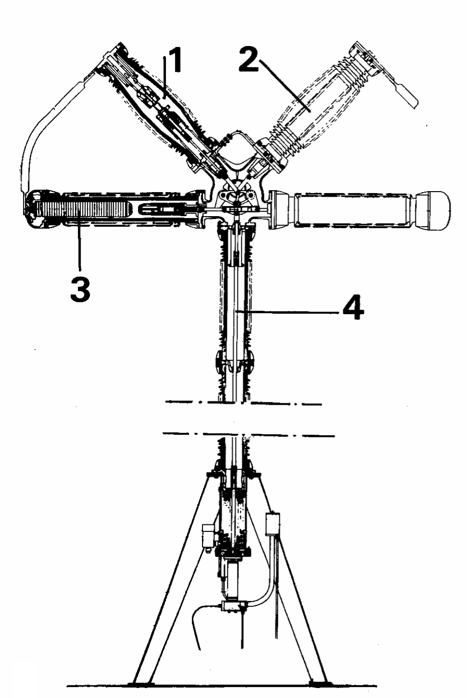

***Fig. 1**: sectional view of a pole unit of 525 kV circuit-breaker equipped with closing resistors.*
1. break
2. grading capacitor
3. closing resistor
4. support insulator

provided to limit the overvoltages during a reclosing operation on a 400 km long 525 kV line to 2.2 p.u., if the line is not compensated, and to 2 p.u., if the line is compensated (see **fig. 2**).

SF_6 puffer circuit-breakers equipped with a set of auxiliary interrupters (see **fig. 3**) incorporating resistors are therefore able to meet the requirement of limitation of reclosing surges, which requirement is of major importance to determine the insulation level of extra-high-voltage systems.

	Non compensated line	Compensated line	
		40 %	70 %
Resistor value (ohms)	360	360	1,000
Insertion time (ms)	10	8.4	10
Overvoltage factor (98 % cumulative probability) p.u.	2.2	2	2

Fig. 2

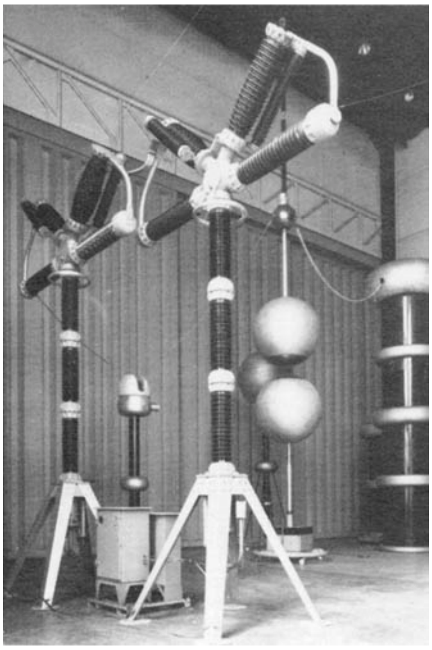

Fig. 3: pole of SF_6 puffer circuit-breaker with 4 breaks and closing resistors.
rated voltage = 525 kV; rated breaking current = 50 kA; rated current = 3,150 A

2.2 De-energisation of open-ended lines

Stresses

The severity of the conditions imposed upon a circuit-breaker when opening an open-ended line may be such that it is these breaking conditions which dictate the size of the circuit-breaker, in particular the selection of the number of breaks. The major fact is that, half a cycle after the interruption, the circuit-breaker must accept a voltage across its terminals at least equal to twice the peak value of the phase-to-earth voltage of the system prior to the interruption. Unfortunately, at the time of opening, it may happen that the phase-to-earth voltage of the pole which has to open has reached values much higher than the values stipulated in the standards for testing the circuit-breaker in such interrupting conditions.

This dynamic voltage rise may be the result of a number of causes. In particular, the opening of a circuit-breaker sited at the receiving end of a line conveying a heavy load will leave the line open at its end. The voltage of the line increases owing to the sudden disappearance of the load that is not immediately compensated by the voltage regulation and owing to the capacitive load constituted by the line. Consequently, the circuit-breaker sited at the sending end may be led to de-energise the line while the phase-to-earth voltage at the sending end has substantially exceeded the normal value.

The special conditions of some systems have evidenced the possibility of high dynamic overvoltages, of about 1.5 p.u., in spite of the favourable effect achieved on the limitation of dynamic overvoltages by compensation reactors. For instance, the phase-to-phase voltages of a 525 kV system and of a 765 kV system may temporarily reach 750 kV and 1,100 kV respectively.

These conditions are exceptional and it is quite normal that such situations are excluded from the verifications stipulated in the standards for line-charging current interruptions. However, the fact that such situations may actually occur has made it necessary to check the ability of the circuit-breakers to withstand such voltages. Even though it can be admitted that such verifications are carried out on the system in the field, the manufacturer must a priori demonstrate the ability of his switchgear.

Test procedures

For system voltages under 245 kV, a direct test can generally be made in a testing station and with an actual line. As soon as the system voltage reaches 420 kV, the direct test becomes more difficult due to the operational conditions often preventing the availability of a no-load line of sufficient length.

Another test procedure consists in simulating the no-load line by means of a capacitor bank. Here again the maximum possibilities of the laboratories are rather rapidly reached considering the size of the bank necessary to obtain the high currents simulating lines of long length with the high voltages previously mentioned. The manufacturer is thus led to perform tests no longer on a complete pole, but on a portion of a pole, even on one break. These tests can be made either on a direct circuit including capacitor banks of high capacitance, or with a synthetic circuit. It is the latter method which we have used with the diagram shown in **Figure 4**. Such a circuit offers the advantage of using only capacitor banks of small size. Indeed, in the "current" circuit, where a high capacitance value is required, a comparatively low voltage is sufficient; in the "voltage" circuit, a capacitance of low value insulated for the full voltage is suitable.

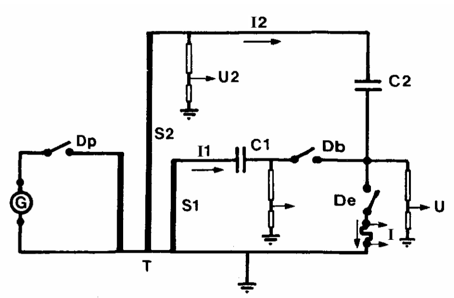

Fig. 4: diagram of synthetic circuit for line-charging current breaking tests.
- Dp: back-up circuit-breaker
- Db: auxiliary circuit-breaker
- De: circuit-breaker under test
- T: transformer with 2 secondary windings
- G: generator
- S1: "current" circuit
- S2: "voltage" circuit
- C1: capacitor bank of "current" circuit
- C2: capacitor bank of "voltage" circuit
- U: recovery voltage at the termmals of De
- I: breakmg current of De
$I = I1 + I2; U = U2 - U_{C2}$

The unit-testing method for the line-charging breaking currents is not explicitly provided for in standards and its application requires some precautions. For circuit-breakers with a short minimum arcing time (this is the case of SF_6 puffer circuit-breakers), the deviation in the simultaneous operation of the breaks of one pole must not exceed 2 ms approximately. The overvoltage on the first break to open must indeed be negligible. A rapid calculation shows that, in the event of a minimum arcing time of 1 ms, a 2 ms deviation involves a 7 percent overvoltage on the first break to open in a 4-interrupter circuit-breaker, and a 12 percent overvoltage in a 6-interrupter circuit-breaker. Consequently this method is quite applicable to the circuit-breaker referred to in this report whose simultaneity of operation of the interrupters is properly ensured and which incorporates only a small number of breaks.

Test results

The tests have been made on a break of the SF_6 puffer circuit-breaker illustrated in figure 3. The tests represent the stress withstood by one break of a 4-break circuit-breaker should the phase-to-phase voltage of the 525 kV system reach 750 kV.

Figure 5 shows the oscillogram of such a breaking operation.

The test voltage is determined by a relationship as follows:

$$U2 = 1.2 \times \frac{750}{\sqrt{3}} \times \frac{1}{4} \text{ kV}$$

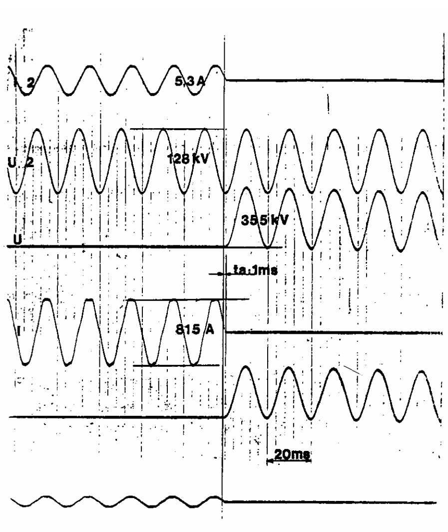

Fig. 5: oscillogram recorded during capacitive current breaking tests on the circuit illustrated in Figure 4.

The tests have been made in compliance with the standards as regards the instant of contact separation. The results are given in the table in **figure 6**.

The results, that do not show any restrike, prove the ability of the circuit-breaker to interrupt no-load lines under the severe conditions described previously.

No.	U2 (kV)	U peak value (kV p)	I (A)	Arcing time (ms)
1	128	345	815	2
2	128	340	815	9
3	128	353	815	8
4	128	340	815	6
5	128	352	815	5
6	128	352	815	3
7	128	353	815	2
8	128	355	815	1
9	128	332	815	9
10	128	340	815	8
11	128	332	815	7
12	128	340	815	5

***Fig. 6**: results of line-charging current breaking tests.*

2.3 De-energisation of shunt reactors

The application of shunt compensating reactors on the lines is practically always necessary in extra-high-voltage systems. Indeed they make it possible to avoid too high over-voltages along the line if this line is at no load or with light load.The extremely favourable influence of compensating reactors on the dynamic overvoltages produced by load rejection at the end of a long line is also known. Lastly, the reactors also have a favourable influence on the limitation of switching surges when closing or reclosing lines at no load. Various possibilities are thus available to benefit from the advantages of shunt reactors:

- the permanent coupling, in parallel with each phase of the line, of an inductor whose value is chosen to be acceptable under all the operating conditions of the system;
- or the connection of the inductor to the line through a circuit-breaker whose controlled closing or opening allows a greater flexibility in the application of the reactor according to the load conveyed by the line (see **Fig. 7**).

These circuit-breakers operate in special conditions since they have to interrupt a small current (a few hundred amperes) and since they operate very frequently. Their mechanical reliability must therefore be very high and they must not generate abnormal overvoltages when breaking this current.
The excellent reliability of SF_6 puffer circuit-breakers has already been mentioned in publications [1] ; it is mainly due to the simplicity of their design.

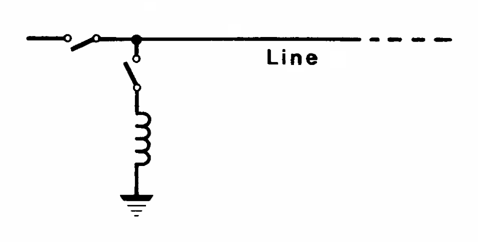

***Fig. 7**: connection diagram of shunt reactors.*

On the contrary, the behaviour of circuit-breakers when breaking small inductive currents is rather poorly known and it appears it is difficult to lay down the corresponding test standards owing to the great number of parameters likely to be involved and to the contingent nature of the results generally obtained.

In addition, it is extremely rare to be in a position in a laboratory to correctly represent the actual operating conditions of the circuit-breakers designed for very high voltages.

Two difficulties are generally encountered:

- test voltage too low;
- inherent capacitances of the test circuit too high.

It is therefore strongly desired to predetermine the overvoltages likely to occur in any operating conditions, on the basis of the results of tests made in definite conditions, if possible with a small number of breaks in series. Some authors have already demonstrated some laws of variation of the chopped current, an overvoltage generator [2]. It will be seen that the results obtained in a testing station with an SF_6 puffer circuit-breaker of the type illustrated in Figure 3 corroborate those laws and that it is thus possible to evaluate the maximum overvoltages likely to be generated by such a circuit-breaker.

Test conditions

Two test series, totalling over 100 breaking operations, were made on several breaks of the circuit-breaker.

In both series, the test circuits were single-phase and their main characteristics were as follows (see **Fig. 8**):

- Series No 1

U = 235 kV
f = 50 Hz
I = 245 - 517 - 1,100 A
C_1 = 1 mF
C_2 = 46 - 127 µF
Number of breaks in series = 3.

- Series No 2

U = 20 - 40 kV
f = 50 Hz
I = 250 - 500 A
C_1 =17 nF
C_2 = 1.9 to 12 nF
Number of breaks in series = 1 or 2.

Series No 1, performed on a 3-interrupter circuit-breaker, is representative of the operation of a 4-interrupter circuit-breaker on a 525 kV power system. The voltage of the test circuit, i.e. 235 kV, was the highest voltage available in the laboratory. During the series, it was not possible to reduce the capacitance of the load-side circuit to a value low enough to be representative of the inherent capacitance of a shunt reactor. Therefore tests were performed at a reduced voltage, with low-value capacitances on the load-side, in order to study the influence of the number of breaks and of the capacitance on the chopped current value.

Test results

Two phenomena are likely to take place when breaking small inductive currents: current chopping and successive re-ignitions (see appendix 1).

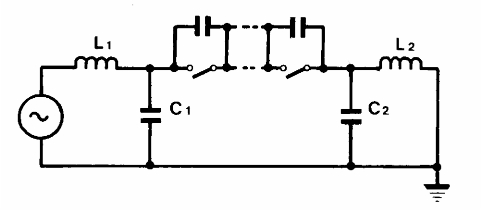

***Fig. 8**: diagram of circuit for inductive current breaking tests.*

During both tests series, current chopping was observed almost systematically, but no breaking operation gave rise to successive re-ignitions. This result is very important because it means that the overvoltages produced by the circuit-breaker can be predetermined with certainty if it is possible to know the law of variation of the chopped current in relation to the parameters of the circuit. Some results previously obtained by the authors during tests of SF_6 puffer circuit-breakers, together with some theoretical and experimental studies already published, show that the chopped current would be determined by a relationship as follows:

$$I_0 = \lambda \sqrt{n\ C'_3} \qquad (6)$$

where Io, is the chopped current, λ a factor specific to the circuit-breaker, expressed in Ampere $(Farad)^{-1/2}$, n the number of breaks in series per pole, C'3, the capacitance in parallel with the pole.

To determine factor λ by means of the test results, only the results obtained for arcing times equal to or greater than 5 ms are taken into account. Shorter arcing times give rise to chopped currents which are not worth studying due to their low values and dispersion, as well as to the inaccuracy of their measurement.

The table in **Figure 9** shows the average values of λ obtained on the different test circuits, each average value being generally calculated on 5 tests. It can be seen that the values thus obtained are very similar, whereas the test conditions cover a very wide range of values for parameters n and C'3; this proves that relationship (6) is quite applicable to this type of circuit-breaker.

Number of interrupters	1	1	1	1	1	2	2	2	2	3	3	3
Voltage (kV)	20	20	20	20	40	20	20	20	40	235	235	235
Breaking current (A)	250	250	250	250	500	250	250	250	500	245	517	1,100
C'_3 (nF)	4.2	5.2	9.2	9.5	9.2	3.9	7.9	8.3	7.9	110	45	47
$\lambda .10^{-3}$	94	89	95	90	92	81	84	96	96	81	74	92

***Fig. 9**: average value of factor λ for arcing times longer than 5 ms.*

Since factor λ does not depend upon the test circuit, it is interesting to analyze its statistical distribution for all the tests under consideration.

Figure 10 represents the histogram of the values of λ and shows a Gaussian distribution :

- the average value $\overline{\lambda} = 88.5 \times 10^3 \ \text{A F}^{-1/2}$;
- the standard deviation $\sigma = 14 \times 10^3 \ \text{A F}^{-1/2}$.

The cumulative frequency curve of l is shown in **Figure 11** in which the normal law corresponding to $\overline{\lambda}$ and σ is also plotted. It can be seen that the distribution of λ follows a normal low, in particular for the values higher than the average value. This makes it possible to calculate the probability of occurrence of high values of chopped current.

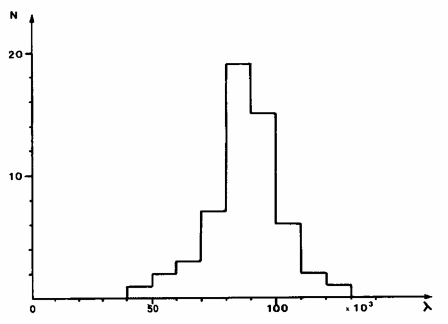

Fig. 10: histogram of factor λ.

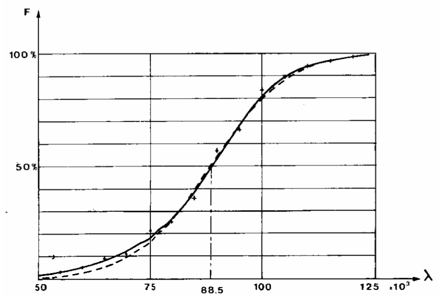

Fig. 11: cumulative frequency of values of factor λ.
—— experimental results
- - - normal law: $\overline{\lambda} = 88.5 \times 10^3$; $\sigma = 14 \times 10^3$

Calculation of overvoltages

In the general case where the source-side capacitance is high compared with the other capacitances of the circuit, the overvoltage factor is given by the following relationship as worked out in appendix 1:

$$k = \sqrt{1 + \frac{n\lambda^2 L_2}{U_m{}^2}} \qquad (10)$$

where L_2 is the load-side inductance and U_m the amplitude of the phase-to-earth voltage.

Since factor λ is known statistically, it is possible to calculate the probability of occurrence of the overvoltages for the 4-break circuit-breaker used to control shunt reactors in a 525 kV power system. For instance, let us consider 3 values of reactance corresponding to single-phase powers of 37, 75 and 150 MVA respectively. When applying the normal law defined in the preceding paragraph to λ, the results listed in the table in **Figure 12** are obtained.

These predetermined overvoltage levels, though based on a comparatively narrow sampling (about 100 tests) nevettheless show that the circuit-breaker under test will not generate abnormally high overvoltages when in service on the power system.

For comparison purposes, tests made on an air-blast circuit-breaker have made it possible to determine an average value of 230 A $F^{-1/2}$ for factor λ, i.e. three times the value corresponding to the SF_6 puffer circuit-breaker. The application of the method of predetermination of inductive-current breaking overvoltages to a 6-break air-blast circuit-breaker, for the values of reactances previously considered, shows that the overvoltage factors would substantially exceed the permissible levels.

Consequently, it would be necessary to limit the overvoltages by means of resistors. In this respect, results of comparative tests performed on Hydro-Quebec power system are available; they show that the de-energisation of reactors by air-blast circuit-breakers not including opening resistors is featured by unacceptable overvoltages.

It is therefore conclusive that this major advantage of the SF_6 puffer circuit-breaker under consideration will be appreciated, since it makes it possible to use a circuit-breaker without resistors for reactor switching, without any risk for the insulation of the reactors.

k			
P	150 MVA	75 MVA	37 MVA
10^{-2}	1.27	1.5	1.87
10^{-3}	1.32	1.57	2
10^{-4}	1.35	1.62	2.07

Fig. 12: calculated probability of overvoltage factors.

3 Transformer secondary fault

3.1 Stresses

The severity imposed upon a circuit-breaker by the conditions produced upon interruption of a short-circuit occurring on the secondary side of a transformer has already been described [3] [4]. It has been demonstrated that the interruption of such a short-circuit, though its magnitude is definltely below the interrupting capability of the circuit-breaker, could cause difficulties to some types of circuit-breakers. In particular, some sensitivity of small-oil-volume circuit-breakers has been explained by the fact that, for comparatively low fault currents, the de-ionizing capacity, which depends upon the magnitude of the breaking current, was not high enough owing to the rate at which the voltage recovers in a circuit oscillating at very high frequency. It has also been noticed that, in some installation conditions, the air-blast circuit-breaker was not in a position to break a short-circuit current corresponding to 40 percent of its breaking current, owing to the value of the recovery voltage frequency that mainly includes the 20 kHz oscillation of a 150 MVA transformer (see **Fig. 13**).

Such situations are more and more frequently encountered in installations fed at voltages from 72.5 kV to 170 kV and their severity increases due to the power rating of the transformers installed. The severity of the breaking conditions also increases with transformers of low impedance voltage that are used for the supply of some industrial installations.

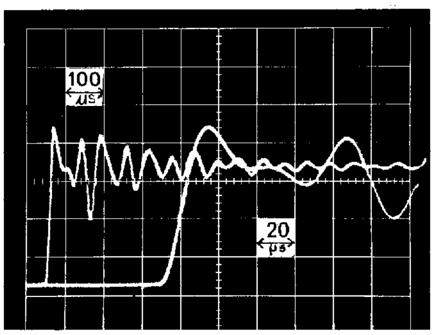

Fig. 13: oscillogram of the TRV recorded during the interruption of a fault on the secondary side of a 220/60 kV transformer.
P= 150 MVA; Impedance voltage = 10.3 percent.

The conclusions drawn from studies conducted on such power systems show that the TRV's recorded with a fault fed through the transformer are definitely more severe than those stipulated in standards for short-circuit currents corresponding to 10 percent and 30 percent of the breaking current. It was therefore important to make sure that the SF_6 puffer circuit-breaker is not led into difficulties in such cases.

3.2 Tests results

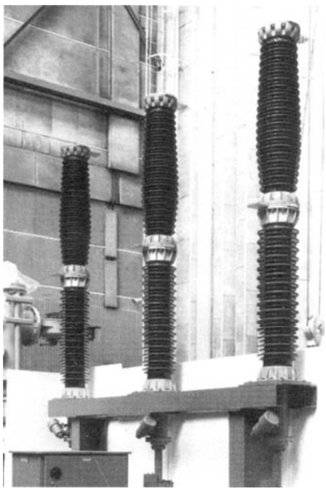

Fig. 14: SF_6 puffer circurt-breaker with 1 break for voltages from 725 kV to170 kV.

The unit under test is a one-break SF_6 puffer circuit-breaker (see **Fig. 14**) intended for use in power systems with voltages from 72.5 to 170 kV. The use of an air reactor, located on the load-side of the circuit-breaker (see **Fig. 15**) allowed the tests to be performed for low current values (1 and 2.5 kA).

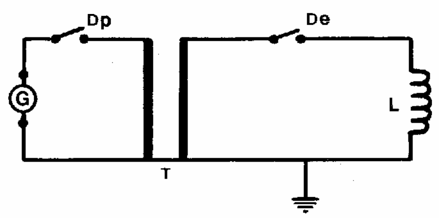

Fig. 15: test circuit including a high reactance on the load-side of the circuit-breaker.

The possibilities of adjustment of the current on the circuit were limited and a current-injection synthetic circuit was used after-wards, for a range of breaking currents from 5 kA to 20 kA.

The table in **Figure 16** summarizes the test conditions and the results.

The tests performed represent severity conditions much in excess of those stipulated in the standards.

The results prove the ability of this circuit-breaker to overcome the most severe stresses likely to take place when faults are fed by powerful transformers, such as encountered in some types of installations.

Tests	Breaking current I (kA)	Number of tests	1st peak voltage U_1 or U_c (kV)	Frequency F (kHz)	T_1 or T_3 (µs)	RRRV (kV/µs)
Tests with reactor on load side	1.1	5	140	17	26	5.4
	2.5	6	85	28	15	5.7
Synthetic tests	5	10	126	33	13.5	9.3
	10	3	126	22	20	6.3
	10	2	126	50	9	14
	15	3	139	22	20	7
	5	3	250	18	24.5	10.2
	10	5	250	18	24.5	10.2
	15	3	250	19	23	10.9
	20	2	250	21	21	11.9

Fig. 16: results of break tests at high frequency.

3.3 Conclusions

It has been shown that, for circuit-breakers used in power systems or industrial installations, exceptional operating conditions may occur, these being widely different from or not yet falling within the scope of standardized conditions.

They are more particulary related to:

- the breaking and making of line charging currents at exceptionally high voltages;
- the breaking of shunt reactor currents;
- the breaking of transformer secondary short-circuit currents.

In each case it has been possible, by laboratory tests, to demonstrate that the SF_6 puffer circuit-breakers under consideration are capable of coping with extremely severe conditions under which circuit-breakers of former technologies could have difficulties.

Appendix: Overvoltages upon low inductive current breaking

The phenomena likely to generate overvoltages upon low inductive current breaking are well known. There are two types as follows:

- premature current interruption, commonly termed "current chopping";
- successive re-ignitions.

These two phenomena can in fact take place successively during the same operation (see **Fig. 17**).

In both cases, the current i_d is interrupted when i_2 is not zero, owing to high frequency oscillations that are superimposed on the power-frequency component of the current in the circuit-breaker.

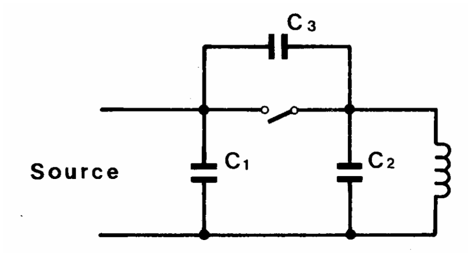

Fig. 17: representative diagram of an inductive current interruption.

Current chopping

Current i_d is interrupted when current i_2 is equal to i_0, and voltage u_2 to U_0 (see **Fig. 18**).
If the damping of the load-side circuit can be considered as negligible during 1/4 cycle of its natural oscillation, the calculation of the over-voltage is straightforward :

$$U_c = \sqrt{U_0^2 + \frac{L_2}{C'_2} I_0^2} \quad (1)$$

where C'_2 is the capacitance in parallel on inductance L_2 after the break:

$$C'_2 = C_2 + \frac{C_1 C_3}{C_1 + C_3} \quad (2)$$

If U_m is the amplitude of the load-side voltage prior to the break:

$$U_o \approx U_m \quad (3)$$

the overvoltage factor $k = \frac{U_c}{U_m}$

is then written as follows:

$$k = \sqrt{1 + \varepsilon^2} \quad (4)$$

where $\varepsilon = \frac{I_0}{U_m} \sqrt{\frac{L_2}{C'_2}} \quad (5)$

It is worth studying term ε when the value of the chopped current confirms the law:

$$I_0 = \lambda \sqrt{n C'_3} \quad (6)$$

where n is the number of breaks in series in one pole and C'_3 the capacitance in parallel in one pole:

$$C'_3 = C_3 + \frac{C_1 C_2}{C_1 + C_2} \quad (7)$$

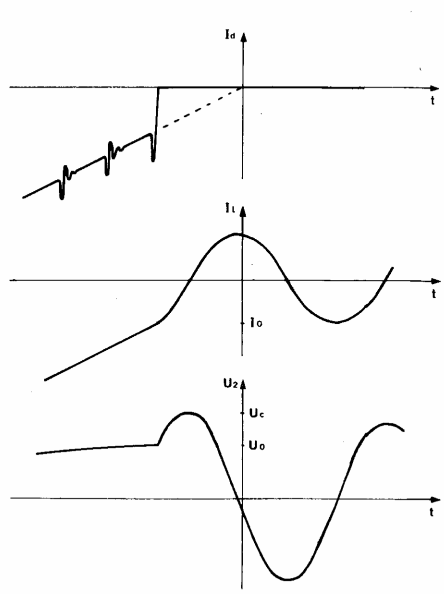

Fig. 18: interruption with current chopping:
i_d: current in circuit-breaker
i_2: current in load-side inductor
u_2: load-side voltage

Relationship (4) becomes:

$$\varepsilon = \frac{\lambda \sqrt{n L_2}}{U_m} \sqrt{\frac{C_1 + C_3}{C_1 + C_2}} \quad (8)$$

As a rule, the values of the capacitances are such that:

$C_1 \gg C_2$ and $C_1 \gg C_3$

Relationship (8) therefore becomes:

$$\varepsilon = \frac{\lambda \sqrt{n L_2}}{U_m} \qquad (9)$$

$$\text{wherefrom } k = \sqrt{1 + \frac{\lambda^2}{U_m{}^2} n L_2} \qquad (10)$$

There is however an upper limit for the value of L_2 beyond which this relationship does not apply any more. This limit is reached when the chopped current is equal to the amplitude of the breaking current.

Finally, if a current chopping takes place without any re-ignition, the overvoltage factor can be predetermined. Moreover, if the source-side capacitance is high compared with the other capacitances, the over-voltage level depends only on the number of breaks per pole and on the value of the load-side inductance, for a given voltage.

Successive re-ignitions

The phenomenon of successive re-ignitions illustrated in **Figure 19** has been described in technical literature [5] . It must essentially be noted that, in this case, the overvoltage is due to the transfer, into the load-side capacitance, of the energy that is re-injected into the load-side circuit on each re-ignition. The highest voltage is not necessarily reached upon final interruption; it may occur earlier, according to the exchange of energy between the source-side circuit and the load-side circuit. The overvoltage level depends on numerous parameters such as:

- the natural frequency of the load-side circuit;
- the point on current wave of contact separation;
- the rate of rise of dielectric strength across contacts;
- the characteristics of the high-frequency current oscillation which in their turn depend upon the distance between the source-side and load-side capacitances.

The nature of some of these parameters gives this phenomenon a very uncertain character and it appears it is very difficult to predetermine the overvoltage level likely to be reached in a given power system. This is still made worse by the interaction which may occur between phases.

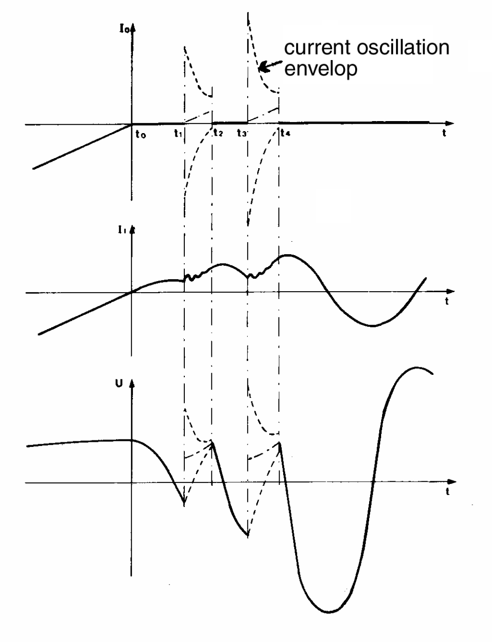

Fig. 19: interruption with repetitive re-ignitions.

Bibliography

[1] "Towards the maintenance-free circuit-breaker"
CIGRE 1974 – Report 13-06.
R. Michaca, J. Verdon, J.C. Okerman, C. Rollier, J. Daillet, B Trolliet.

[2] "Switching of shunt reactors-comparison between field and laboratory tests"
CIGRE 1976 – Report 13-04.
S. Berneryd, C.E. Solver, R. Erikson, L. Ahlgren.

[3] "Transient recovery voltage conditions to be expected when interrupting short-circuit currents limited by transformers"
CIGRE 1970 - Report 13-07.
Study Committee No. 13.

[4] "Transient recovery voltage associated with power system, three-phase transformer secondary faults.
IEEE PAS 91 - September/October 1972, pages 1887 to 1896.
R. Harner and J. Rodriguez.

[5] "A comparison of overvoltage phenomena in high-voltage vacuum and air-break switches"
Cahier Technique no. 66.
J.L. Mircovich, G. Perrissin.

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